ITERATIVE MMSE RECEIVERS FOR MULTIUSER MIMO COOPERATIVE SYSTEMS

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ABSTRACT

In this work we study a two-user multiple antenna system under quasi-static fading employing a novel scheme that combines cooperation and iterative multiuser detection based on minimum mean square error estimation. We investigate three different receivers: a joint detector for the two users, a separate (per-user) detector, and a distributed matrix-Alamouti detector. We show that the separate detector and the distributed matrix-Alamouti have close performance but different detection complexity depending on the antenna configuration. Frame error rate performance under Monte Carlo simulations is finally shown.

1. INTRODUCTION

Wireless-communication systems have received a large interest in the past years, thus their design is in continuous evolution. Slow fading severely degrades their performance, and providing diversity to the system is among the main techniques to combat fading [17]. Multi-antenna systems have shown to increase diversity and/or capacity [15, 16], with many different solutions proposed depending on the specific Multiple-Input Multiple-Output (MIMO) scenario [17]. Moreover, user cooperation [13, 14] represents another popular technique for spatial diversity, as it provides virtual multiple-antenna arrays with single-antenna users. Various protocols have been studied in the literature, such as *amplify-and-forward* and *decode-and-forward* [8, 9], or *coded cooperation* [5].

MultiUser Detection (MUD) is a largely used technique in interfering scenarios [18], and iterative MUD receivers achieve almost optimum performance over Gaussian channels with contained complexity [3, 19]. *A posteriori* probability (APP) detection, optimal but exponentially complex, is usually replaced with Parallel Interference Cancellation (PIC) and Minimum Mean Square Error (MMSE) filtering.

In this paper we propose and compare three different MUD schemes in an iterative receiver for cooperative MIMO systems under slow-fading: (i) a Joint-Detection (JD) scheme in which all the received and desired information are processed jointly (this approach is optimum when using APP detection, but is very poor performing with PIC and MMSE filtering, as shown in the sequel); (ii) a Separate-Detection (SD) scheme

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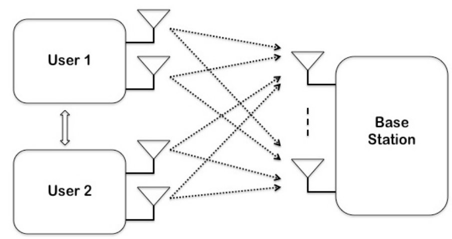

Fig. 1. Two-user cooperative scenario.

in which the information related to each user is treated separately; (iii) a scheme based on the Alamouti scheme [1], called “Distributed Matrix Alamouti” (DMA) scheme [6, 7], in which inter-user interference is partially removed by means of Alamouti combining at the receiver. The novel contribution is to combine MUD techniques into a cooperative protocol in order to increase the information rate of the system. Differently from classical cooperation, after the information of each user has been made available to the partner via orthogonal transmission, both users relay the partner information simultaneously, thus implementing a multiuser interfering transmission. DMA and linear MUD techniques are exploited to achieve excellent performance with contained complexity.

The outline of the paper is as follows: in Sec. 2 we present the system model under investigation, while in Sec. 3 we derive the equations corresponding to the three receivers. Sec. 4 highlights their performance obtained via numerical simulations, and finally Sec. 5 gives the concluding remarks.

Notation – Lower-case bold letters denote vectors, with a_n denoting the nth element of the vector $\boldsymbol{a}$; upper-case bold letters denote matrices, with $A_{n,m}$ denoting the (n,m)th element of the matrix $\boldsymbol{A}$; $\boldsymbol{I}_N$ denotes the $N \times N$ identity matrix, and $\boldsymbol{e}_N^{(n)}$ is the nth column of the matrix $\boldsymbol{I}_N$; $\boldsymbol{0}_{N\times M}$ denotes the $N \times M$ null matrix; $\mathrm{diag}(\boldsymbol{a})$ denotes a diagonal matrix with the vector $\boldsymbol{a}$ on the main diagonal; $\mathbb{E}\{\cdot\}$, $(\cdot)^*$, $(\cdot)^t$ and $(\cdot)^\dagger$ denote expectation, conjugate, transpose and conjugate transpose operators; $\delta_{n,m}$ denotes the Kronecker delta; $\otimes$ denotes the Kronecker matrix product; $\boxtimes$ is a matrix product such that $\boldsymbol{A} \boxtimes \boldsymbol{B} = \left(\boldsymbol{A} \otimes (\boldsymbol{B}\boldsymbol{e}_N^{(1)}), \ldots, \boldsymbol{A} \otimes (\boldsymbol{B}\boldsymbol{e}_N^{(N)})\right)$ with $\boldsymbol{B}$ having N columns; $\mathrm{vec}(\boldsymbol{A})$ is a vector containing the elements of $\boldsymbol{A}$ stacked column-by-column.

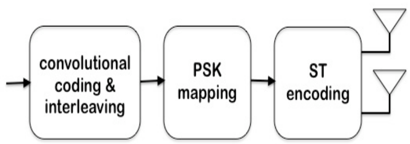

Fig. 2. Block diagram of the transmitter.

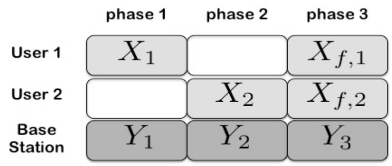

Fig. 3. Structure of the cooperation frame.

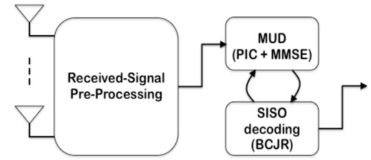

Fig. 4. Block diagram of the receiver.

2. SYSTEM MODEL

We consider a system with two users and one base station in the uplink communication mode as shown in Fig. 1. Each user is equipped with n_t antennas, while the base station is equipped with n_r antennas. The users transmit their own information to the base station and they cooperate to send each others information. We consider half-duplex transmission, in which user terminals cannot transmit and receive simultaneously. The cooperative protocol is the decode-and-forward protocol, in which users decode each others signals before forwarding to the base station. We consider a quasi-static fading channel, in which a codeword sees a single channel realization between a given pair of transmit/receive antennas. First of all, each user independently encodes a group of L_b bits of information using a rate-R convolutional code and a bit interleaver, as depicted in Fig. 2.

The resulting channel codeword of pL code bits is mapped into a string of L complex symbols, $(z_1, \ldots, z_L)$, using a 2^p−PSK modulation. In the presence of a space-time encoder, the string is divided into G groups, each containing $M = sn_t$ symbols (s being the time spreading factor of the unitary space-time rotation $\boldsymbol{S}$), i.e. $(z_1(g), \ldots, z_M(g))$ with $g = 1, \ldots, G$ and such that $z_l(g) = z_{(g-1)M+l}$. Omitting the index g for sake of simplicity, each group is independently processed as follows. Modulated symbols are placed in a matrix $\boldsymbol{Z}$ of size $n_t \times s$. The space-time rotation $\boldsymbol{S}$ of size $sn_t \times sn_t$ is then applied to $\boldsymbol{Z}$ in order to obtain the space-time codeword $\boldsymbol{X}$ of size $n_t \times s$ such that

$$\mathrm{vec}\left(\boldsymbol{X}^t\right) = \boldsymbol{S}\, \mathrm{vec}\left(\boldsymbol{Z}^t\right) \;, \tag{1}$$

where the complex symbol $X_{j,\ell}$ is transmitted over the wireless channel by the jth antenna during the ℓth time slot. Note that in the absence of a space-time rotation, we have that $s = 1$ and $\boldsymbol{S} = \boldsymbol{I}_{n_t}$.

The cooperation frame of the proposed scheme is shown in Fig. 3. It consists of three phases each involving s time slots. In phase, user 1 broadcasts its symbols $\boldsymbol{X}_1$ to both user 2 and the base station. In the second phase, user 2 transmits its symbols $\boldsymbol{X}_2$ to both user 1 and the base station. In the last phase, after having decoded each others information, user 2 sends $\boldsymbol{X}_{f2}$ (user 1 symbols) and user 1 sends $\boldsymbol{X}_{f1}$ (user 2 symbols) simultaneously to the base station. As shown in the next section, the expression for $\boldsymbol{X}_{f1}$ and $\boldsymbol{X}_{f2}$ can vary according to the scheme used. In the sequel, we will consider that each user decodes the others symbols perfectly, which is a realistic situation in the sense that cooperation usually takes place between terminals that are separated by reliable channels. The received matrices at the base station are given by:

$$\boldsymbol{Y}_1 = \boldsymbol{H}_1\boldsymbol{X}_1 + \boldsymbol{W}_1 \;, \tag{2}$$

$$\boldsymbol{Y}_2 = \boldsymbol{H}_2\boldsymbol{X}_2 + \boldsymbol{W}_2 \;, \tag{3}$$

$$\boldsymbol{Y}_3 = \boldsymbol{H}_1\boldsymbol{X}_{f1} + \boldsymbol{H}_2\boldsymbol{X}_{f2} + \boldsymbol{W}_3 \;, \tag{4}$$

where $\boldsymbol{X}_i \in \Omega = (2^p - \text{PSK})^{sn_t}$ have dimensions $n_t \times s$, $\boldsymbol{H}_i$ are the $n_r \times n_t$ matrices of complex i.i.d circularly symmetric Gaussian coefficients with zero mean and unit variance between user i and the base station, and $\boldsymbol{W}_i$ are the $n_r \times s$ matrices of circularly symmetric complex AWGN components with zero mean and variance η_0. The channel outputs $\boldsymbol{Y}_j$ are thus the $n_r \times s$ matrices of received symbols in the j^{th} phase of the cooperation frame. We consider perfect channel knowledge at the receiver and perfect synchronization.

3. ITERATIVE MMSE RECEIVERS

The iterative receiver at the base station consists of three blocks as in Fig. 4. The first block pre-processes the received signals in order to provide suitable information for MUD. The MUD block aims to unveil the contributions of each complex symbol from the received signal. The soft-input soft-output (SISO) decoder performs the decoding of the convolutional codewords for each user via the BCJR algorithm [2]. The receiver is iterative because MUD and SISO blocks iteratively exchange their soft information before the final decision.

In this section, we derive three receiver schemes with varying complexity under MMSE filtering. In the following $\tilde{\boldsymbol{Z}} = \mathbb{E}\{\boldsymbol{Z}\}$ is assumed to be available from the SISO decoders, and is assumed to be null at first iteration.

3.1. Scheme 1: Joint Detector (JD)

For this scheme the users decode, re-encode, and transmit each others information to the base station, we thus set $\boldsymbol{X}_{f1} = \boldsymbol{X}_2$ and $\boldsymbol{X}_{f2} = \boldsymbol{X}_1$ in (4). The joint detector consists of applying an MMSE filter to the overall channel seen by the two users. We can thus describe (2)-(4) in one equation where $\boldsymbol{Y} = (\boldsymbol{Y}_1^t, \boldsymbol{Y}_2^t, \boldsymbol{Y}_3^t)^t$ and $\boldsymbol{W} = (\boldsymbol{W}_1^t, \boldsymbol{W}_2^t, \boldsymbol{W}_3^t)^t$ are the received signal for both users and the matrix of noise components, $\boldsymbol{X} = (\boldsymbol{X}_1^t, \boldsymbol{X}_2^t)^t$ is the joint transmitted signal, and

$$\boldsymbol{H} = \begin{pmatrix} \boldsymbol{H}_1 & \boldsymbol{0}_{n_r \times n_t} \\ \boldsymbol{0}_{n_r \times n_t} & \boldsymbol{H}_2 \\ \boldsymbol{H}_2 & \boldsymbol{H}_1 \end{pmatrix} \;.$$

Alternatively, in vector form, we get:

$$\boldsymbol{y} = \breve{\boldsymbol{H}}\boldsymbol{z} + \boldsymbol{w} \ , \tag{5}$$

where $\boldsymbol{y} = \mathrm{vec}\left(\boldsymbol{Y}^t\right)$ and $\boldsymbol{w} = \mathrm{vec}\left(\boldsymbol{W}^t\right)$ are the length-$3sn_r$ vectors of received symbols and AWGN components, $\boldsymbol{z} = \mathrm{vec}\left(\boldsymbol{Z}_1^t, \boldsymbol{Z}_2^t\right)$ of length $2sn_t$ contains the symbols from both users, and finally where $\breve{\boldsymbol{H}} = \left(\boldsymbol{H} \otimes \boldsymbol{I}_s\right)\left(\boldsymbol{I}_2 \otimes \boldsymbol{S}\right)$ with dimensions $3sn_r \times 2sn_t$.

Based on (5), it is possible to estimate the complex symbols z_m transmitted by the two users[1]. Let $\hat{\boldsymbol{z}}$ denote the estimate of $\boldsymbol{z}$, and define $\tilde{\boldsymbol{z}}_{(m)} = \tilde{\boldsymbol{z}} - \tilde{z}_m \boldsymbol{e}_{2sn_t}^{(m)}$ a vector containing the interference experienced by the mth symbol, i.e.

$$\tilde{z}_{(m)n} = \begin{cases} \tilde{z}_{(m)n} & n \neq m \\ 0 & n = m \end{cases} .$$

The unbiased estimation of z_m, obtained via PIC and MMSE filtering along the same lines in [11, 12], is

$$\hat{z}_m = \frac{\breve{\boldsymbol{h}}_{(m)}^{\dagger} \left(\breve{\boldsymbol{H}} \mathrm{diag}(\boldsymbol{v}_{(m)}) \breve{\boldsymbol{H}}^{\dagger} + \eta_o \boldsymbol{I}_{3sn_r} \right)^{-1} \tilde{\boldsymbol{y}}_{(m)}}{\breve{\boldsymbol{h}}_{(m)}^{\dagger} \left(\breve{\boldsymbol{H}} \mathrm{diag}(\boldsymbol{v}_{(m)}) \breve{\boldsymbol{H}}^{\dagger} + \eta_o \boldsymbol{I}_{3sn_r} \right)^{-1} \breve{\boldsymbol{h}}_{(m)}} ,$$

where $\breve{\boldsymbol{h}}_{(m)} = \breve{\boldsymbol{H}} \boldsymbol{e}_{2sn_t}^{(m)}$, and $\tilde{\boldsymbol{y}}_{(m)} = \boldsymbol{y} - \breve{\boldsymbol{H}} \tilde{\boldsymbol{z}}_{(m)}$ represents the residual term from PIC, and $\boldsymbol{v}_{(m)}$ takes into account the variance of the soft information from the SISO decoders

$$v_{(m)n} = \begin{cases} 1 - |\tilde{z}_n|^2 & n \neq m \\ 1 & n = m \end{cases} .$$

3.2. Scheme 2 : Separate (per-user) Detector (SD)

As in the previous scheme, we set $\boldsymbol{X}_{f1} = \boldsymbol{X}_2$ and $\boldsymbol{X}_{f2} = \boldsymbol{X}_1$ in (4). We then merge (2)-(4) into two equations as follows:

$$\boldsymbol{Y}[u] = \boldsymbol{H}[u]\boldsymbol{X}_u + \boldsymbol{K}[u]\boldsymbol{Q}_u + \boldsymbol{W}[u] \ , \qquad u = 1, 2, \tag{6}$$

where $\boldsymbol{Y}[u] = \left(\boldsymbol{Y}_u^t, \boldsymbol{Y}_3^t\right)^t$ and $\boldsymbol{W}[u] = \left(\boldsymbol{W}_1^t, \boldsymbol{W}_3^t\right)^t$ are the $2n_r \times s$ matrices of received symbols and AWGN components for the uth user, $\boldsymbol{Q}_1 = \boldsymbol{X}_2$ and $\boldsymbol{Q}_2 = \boldsymbol{X}_1$ denote the signals from the interfering user, and finally $\boldsymbol{H}[1] = \left(\boldsymbol{H}_1^t, \boldsymbol{H}_2^t\right)^t$, $\boldsymbol{H}[2] = \left(\boldsymbol{H}_2^t, \boldsymbol{H}_1^t\right)^t$, and $\boldsymbol{K}[1] = \left(\boldsymbol{0}_{n_t \times n_r}, \boldsymbol{H}_1^t\right)^t$, $\boldsymbol{K}[2] = \left(\boldsymbol{0}_{n_t \times n_r}, \boldsymbol{H}_2^t\right)^t$. Rewriting (6) in vector form, we get:

$$\boldsymbol{y}_u = \boldsymbol{A}_u \boldsymbol{z}_u + \boldsymbol{B}_u \boldsymbol{q}_u + \boldsymbol{w}_u \ , \qquad u = 1, 2 \ , \tag{7}$$

where $\boldsymbol{y}_u = \mathrm{vec}\left(\boldsymbol{Y}[u]^t\right)$ is the separate received signal, $\boldsymbol{w}_u = \mathrm{vec}\left(\boldsymbol{W}[u]^t\right)$, $\boldsymbol{z}_u = \mathrm{vec}\left(\boldsymbol{Z}_u^t\right)$ contains the symbol from the user of interest, $\boldsymbol{q}_u = \mathrm{vec}\left(\boldsymbol{Q}[u]^t\right)$ contains the interfering symbols, with $\boldsymbol{A}_u = \left(\boldsymbol{H}[u] \otimes \boldsymbol{I}_s\right) \boldsymbol{S}$ and $\boldsymbol{B}_u = \left(\boldsymbol{K}[u] \otimes \boldsymbol{I}_s\right) \boldsymbol{S}$.

[1] It is worth noticing that here $m = 1, \ldots, 2sn_t$ spans all the symbols that produce two space-time codewords (one per user).

Omitting the user index u, the unbiased estimation of z_m, again obtained via PIC and MMSE filtering, is

$$\hat{z}_m = \frac{\boldsymbol{a}_{(m)}^{\dagger} \left(\boldsymbol{A} \mathrm{diag}(\boldsymbol{v}_{(m)}) \boldsymbol{A}^{\dagger} + \boldsymbol{B} \mathrm{diag}(\boldsymbol{u}) \boldsymbol{B}^{\dagger} + \eta_o \boldsymbol{I}_{2sn_r} \right)^{-1} \tilde{\boldsymbol{y}}_{(m)}}{\boldsymbol{a}_{(m)}^{\dagger} \left(\boldsymbol{A} \mathrm{diag}(\boldsymbol{v}_{(m)}) \boldsymbol{A}^{\dagger} + \boldsymbol{B} \mathrm{diag}(\boldsymbol{u}) \boldsymbol{B}^{\dagger} + \eta_o \boldsymbol{I}_{2sn_r} \right)^{-1} \boldsymbol{a}_{(m)}} ,$$

where $\boldsymbol{a}_{(m)} = \boldsymbol{A} \boldsymbol{e}_{sn_t}^{(m)}$, and $\tilde{\boldsymbol{y}}_{(m)} = \boldsymbol{y} - \boldsymbol{A} \tilde{\boldsymbol{z}}_{(m)} - \boldsymbol{B} \tilde{\boldsymbol{q}}$ represents the residual term from PIC, with $\boldsymbol{z}_{(m)} = \tilde{\boldsymbol{z}} - \tilde{z}_m \boldsymbol{e}_{n_t}^{(m)}$, and where $u_n = 1 - |\tilde{q}_n|^2$, and

$$v_{(m)n} = \begin{cases} 1 - |\tilde{z}_n|^2 & n \neq m \\ 1 & n = m \end{cases} .$$

3.3. Scheme 3 : DMA Detector (DMAD)

In [6], an extension of the Alamouti scheme for more than two transmit antennas has been proposed for MIMO systems. Later, the same scheme has been studied for distributed communication systems under optimal *a posteriori* probability (APP) detection [7]. We investigate here this scheme under MMSE detection. We first write $\boldsymbol{X}_{f1} = -\boldsymbol{X}_2^*$ and $\boldsymbol{X}_{f2} = \boldsymbol{X}_1^*$ in (4). Before applying PIC and MMSE filtering, the received signals in (2)-(4) are first processed using the Alamouti decoupling equations as:

$$\begin{aligned} \boldsymbol{R}_1 &= \boldsymbol{H}_1^{\dagger}(\boldsymbol{Y}_1 + \boldsymbol{Y}_2) + \boldsymbol{Y}_3^{\dagger} \boldsymbol{H}_2 \\ &= \left(\boldsymbol{H}_1^{\dagger}\boldsymbol{H}_1\right) \boldsymbol{X}_1 + \boldsymbol{X}_1^t \left(\boldsymbol{H}_2^{\dagger}\boldsymbol{H}_2\right) \\ &\quad + \left(\boldsymbol{H}_1^{\dagger}\boldsymbol{H}_2\right) \boldsymbol{X}_2 - \boldsymbol{X}_2^t \left(\boldsymbol{H}_1^{\dagger}\boldsymbol{H}_2\right) \\ &\quad + \left(\boldsymbol{H}_1^{\dagger}(\boldsymbol{W}_1 + \boldsymbol{W}_2) + \boldsymbol{W}_3^{\dagger}\boldsymbol{H}_2\right) , \end{aligned} \tag{8}$$

$$\begin{aligned} \boldsymbol{R}_2 &= \boldsymbol{H}_2^{\dagger}(\boldsymbol{Y}_1 + \boldsymbol{Y}_2) - \boldsymbol{Y}_3^{\dagger} \boldsymbol{H}_1 \\ &= \left(\boldsymbol{H}_2^{\dagger}\boldsymbol{H}_2\right) \boldsymbol{X}_2 + \boldsymbol{X}_2^t \left(\boldsymbol{H}_1^{\dagger}\boldsymbol{H}_1\right) \\ &\quad + \left(\boldsymbol{H}_2^{\dagger}\boldsymbol{H}_1\right) \boldsymbol{X}_1 - \boldsymbol{X}_1^t \left(\boldsymbol{H}_2^{\dagger}\boldsymbol{H}_1\right) \\ &\quad + \left(\boldsymbol{H}_2^{\dagger}(\boldsymbol{W}_1 + \boldsymbol{W}_2) - \boldsymbol{W}_3^{\dagger}\boldsymbol{H}_1\right) . \end{aligned} \tag{9}$$

The matrix operations in the above decoupling equations impose that $s = n_t$ so that the resulting matrices of transmitted symbols are squared. As stated in [6, 7], matrix product being not commutative, interference is not totally removed through Alamouti decoupling. The remaining interference is thus removed using an iterative receiver.

We write the received (or processed) signal equations similarly to (6). First, we keep (2) and (3) in the form

$$\boldsymbol{r}_u' = \boldsymbol{A}_u' \boldsymbol{z}_u + \boldsymbol{w}_u' \ , \qquad u = 1, 2 \ , \tag{10}$$

where $\boldsymbol{r}_u' = \mathrm{vec}\left(\boldsymbol{Y}_u^t\right)$, $\boldsymbol{w}_u' = \mathrm{vec}\left(\boldsymbol{W}_u^t\right)$, $\boldsymbol{z}_u = \mathrm{vec}\left(\boldsymbol{Z}_u^t\right)$ contains the symbol from the user of interest, and $\boldsymbol{A}_u' = \left(\boldsymbol{H}_u \otimes \boldsymbol{I}_{n_t}\right) \boldsymbol{S}$. Next, (8) and (9) in vector form as:

$$\boldsymbol{r}_u'' = \boldsymbol{A}_u'' \boldsymbol{z}_u + \boldsymbol{B}_u'' \boldsymbol{q}_u + \boldsymbol{w}_u'' \ , \qquad u = 1, 2 \ , \tag{11}$$

where $\boldsymbol{r}''_u = \text{vec}\left(\boldsymbol{R}^t_u\right)$ $\boldsymbol{q}_1 = \boldsymbol{z}_2$ and $\boldsymbol{q}_2 = \boldsymbol{z}_1$ are the interfering symbols, and where

$$\begin{aligned}
\boldsymbol{A}''_1 &= \left[\left(\boldsymbol{H}^\dagger_1\boldsymbol{H}_1\right) \otimes \boldsymbol{I}_{n_t}\right) + \left(\boldsymbol{I}_{n_t} \boxtimes \left(\boldsymbol{H}^t_2\boldsymbol{H}^*_2\right)\right] \boldsymbol{S} \,, \\
\boldsymbol{B}''_1 &= \left[\left(\boldsymbol{H}^\dagger_1\boldsymbol{H}_2\right) \otimes \boldsymbol{I}_{n_t}\right) - \left(\boldsymbol{I}_{n_t} \boxtimes \left(\boldsymbol{H}^t_2\boldsymbol{H}^*_1\right)\right] \boldsymbol{S} \,, \\
\boldsymbol{w}''_1 &= \text{vec}\left[(\boldsymbol{W}_1 + \boldsymbol{W}_2)^t\boldsymbol{H}^*_1 + \boldsymbol{H}^t_2\boldsymbol{W}^*_3\right] \,, \\
\boldsymbol{A}''_2 &= \left[\left(\boldsymbol{H}^\dagger_2\boldsymbol{H}_2\right) \otimes \boldsymbol{I}_{n_t}\right) + \left(\boldsymbol{I}_{n_t} \boxtimes \left(\boldsymbol{H}^t_1\boldsymbol{H}^*_1\right)\right] \boldsymbol{S} \,, \\
\boldsymbol{B}''_2 &= \left[\left(\boldsymbol{H}^\dagger_2\boldsymbol{H}_1\right) \otimes \boldsymbol{I}_{n_t}\right) - \left(\boldsymbol{I}_{n_t} \boxtimes \left(\boldsymbol{H}^t_1\boldsymbol{H}^*_2\right)\right] \boldsymbol{S} \,, \\
\boldsymbol{w}''_2 &= \text{vec}\left[(\boldsymbol{W}_1 + \boldsymbol{W}_2)^t\boldsymbol{H}^*_2 - \boldsymbol{H}^t_1\boldsymbol{W}^*_3\right] \,.
\end{aligned}$$

It is also straightforward to compute the noise covariance matrices $\boldsymbol{\Sigma}_u = \mathbb{E}\left\{\boldsymbol{w}''_u\boldsymbol{w}''^\dagger_u\right\}$ as

$$\begin{aligned}
\boldsymbol{\Sigma}_1 &= \left(\left(\boldsymbol{H}^\dagger_1\boldsymbol{H}_1\right) \otimes (2\eta_o\boldsymbol{I}_{n_t})\right) + \left((\eta_o\boldsymbol{I}_{n_t}) \otimes \left(\boldsymbol{H}^t_2\boldsymbol{H}^*_2\right)\right) \,, \\
\boldsymbol{\Sigma}_2 &= \left(\left(\boldsymbol{H}^\dagger_2\boldsymbol{H}_2\right) \otimes (2\eta_o\boldsymbol{I}_{n_t})\right) + \left((\eta_o\boldsymbol{I}_{n_t}) \otimes \left(\boldsymbol{H}^t_1\boldsymbol{H}^*_1\right)\right) \,.
\end{aligned}$$

Although the noise in the equivalent model of (11) may appear correlated, it is easy to see that its statistics (averaged on different channel realization) follow a white structure due to the Hermitian matrices involved, i.e. $\boldsymbol{w}''_u$ is a vector of circularly symmetric AWGN components of zero mean and variance $3\eta_o$. By combining (10) and (11), we get the expression described by (7), where $\boldsymbol{y}_u = \left(\boldsymbol{r}'^{\,t}_u, \boldsymbol{r}''^t_u\right)^t$, $\boldsymbol{A}_u = \left(\boldsymbol{A}'^{\,t}_u, \boldsymbol{A}''^t_u\right)^t$, $\boldsymbol{B}_u = \left(\boldsymbol{0}_{n_t^2 \times n_r n_t}, \boldsymbol{B}''^t_u\right)^t$, and

$$\boldsymbol{\Sigma}_u = \mathbb{E}\left\{\boldsymbol{w}_u\boldsymbol{w}^\dagger_u\right\} = \begin{pmatrix} \eta_o\boldsymbol{I}_{n_r n_t} & \boldsymbol{0}_{n_r n_t \times n_t^2} \\ \boldsymbol{0}_{n_t^2 \times n_r n_t} & 3\eta_0\boldsymbol{I}_{n_t^2} \end{pmatrix} .$$

Omitting the user index u, the unbiased estimation of z_m, again obtained via PIC and MMSE filtering, is

$$\hat{z}_m = \frac{\boldsymbol{a}^\dagger_{(m)}\left(\boldsymbol{A}\text{diag}(\boldsymbol{v}_{(m)})\boldsymbol{A}^\dagger + \boldsymbol{B}\text{diag}(\boldsymbol{u})\boldsymbol{B}^\dagger + \boldsymbol{\Sigma}\right)^{-1}\tilde{\boldsymbol{y}}_{(m)}}{\boldsymbol{a}^\dagger_{(m)}\left(\boldsymbol{A}\text{diag}(\boldsymbol{v}_{(m)})\boldsymbol{A}^\dagger + \boldsymbol{B}\text{diag}(\boldsymbol{u})\boldsymbol{B}^\dagger + \boldsymbol{\Sigma}\right)^{-1}\boldsymbol{a}_{(m)}} \,,$$

where $\boldsymbol{a}_{(m)} = \boldsymbol{A}\boldsymbol{e}^{(m)}_{n_t^2}$, and $\tilde{\boldsymbol{y}}_{(m)} = \boldsymbol{y} - \boldsymbol{A}\tilde{\boldsymbol{z}}_{(m)} - \boldsymbol{B}\tilde{\boldsymbol{q}}$ represents the residual term from PIC, with $\boldsymbol{z}_{(m)} = \tilde{\boldsymbol{z}} - \tilde{z}_m\boldsymbol{e}^{(m)}_{n_t^2}$, and where $u_n = 1 - |\tilde{q}_n|^2$, and

$$v_{(m)n} = \begin{cases} 1 - |\tilde{z}_n|^2 & n \neq m \\ 1 & n = m \end{cases} .$$

To conclude this section, it is worth noticing that a matrix inversion within the MMSE filters of the three scheme is required for each transmitted symbol and at each iteration. The size of the matrix to invert may be considered as an indicator of the complexity of the receiver. Tab. 1 shows the size of such matrices for the three schemes presented when assuming space-time rotation (i.e. $s = n_t = 2$). In the next section, it will be shown that both the JD and SD schemes have very poor performance when choosing $s = 1$.

Table 1. Size of the matrix to invert within the MMSE filter.

JD	$3n_tn_r \times 3n_tn_r$
SD	$2n_tn_r \times 2n_tn_r$
DMAD	$n_t\left(n_t + n_r\right) \times n_t\left(n_t + n_r\right)$

4. SIMULATION RESULTS

In this section, the three schemes are compared in terms of frame error rate (FER) versus signal-to-noise ratio (SNR). Moreover, comparison is made with the orthogonal separate detection (O-SD) scheme, in which the third phase of the cooperation frame is replaced with two phases in which the two users alternatively act as relay for the partner, thus resulting in four phases. For this reason, the scheme of Section 3.2 is denoted non-orthogonal SD (NO-SD) in this section. Simulations have been run for systems with $n_t = 2$ per user and both $n_r = 2$ (shown in Fig. 5) and $n_r = 4$ (shown in Fig. 6) over quasi-static fading channels. A frame contains $N = 256$ Quadrature Phase Shift Keying (QPSK) modulated symbols, and modified cyclotomic space-time rotations [4] that are optimal for both iterative decoding under APP detection and MMSE detection [10] are used. The error-correcting code used is the half-rate 16-state $(23, 35)_8$ non-recursive non-systematic convolutional (NRNSC) code and the interleavers are the optimized interleavers from [4].

Both figures show comparisons between the four schemes. In addition, Fig. 5 shows the performance of the NO-SD and the JD schemes with unrotated constellation in order to emphasize the role of the space-time rotation on the system performance: it is apparent that a space-time rotation is necessary for both the SD and JD schemes to exploit more diversity from the channel and thus to obtain an error rate that significantly decreases with the SNR in the range considered. However, even with space-time rotations, the JD scheme presents poor performance with a high detection complexity, although this scheme has shown to be optimal under APP detection [7]. The NO-SD scheme with rotation slightly outperforms the DMAD scheme (less than 1.5 dB at FER$= 10^{-3}$), while the O-SD scheme with a rotation has intermediate performance. In Fig. 6, the behavior is almost the same as with $n_r = 2$, with the difference of a steeper FER curve slope due to the increase in the number of receive antennas, and with a higher separation between the NO-SD and the O-SD schemes.

It is worth noticing that, although the FER performance of DMAD, NO-SD, and O-SD schemes are similar in terms of FER-vs-SNR, the DMAD and the NO-SD schemes require $3/4$ of the transmission time that the O-SD scheme needs to transmit the same amount of data, thus the last scheme would result very inefficient in terms of throughput. Finally, the detection complexity (i.e. the size of the matrix to invert within the MMSE filter) increases linearly with respect to both n_t and n_r for the NO-SD scheme, while for the DMAD scheme it increases linearly with respect to n_r and quadratically with

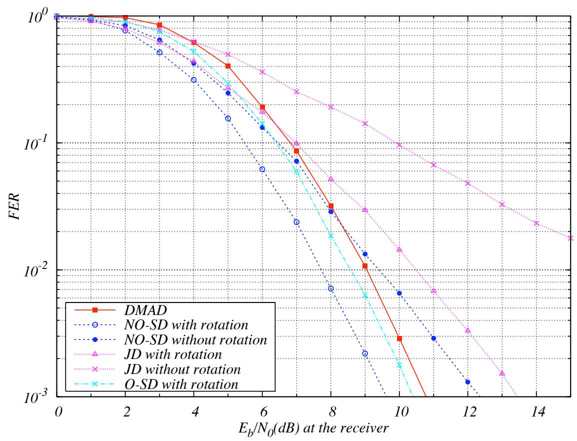

Fig. 5. Cooperative multiple-access schemes with MMSE detectors, $n_t = 2$ per user, $n_r = 2$, $N = 256$, $R_c = 1/2$ 16-state $(23, 35)_8$ NRNSC code, QPSK modulation.

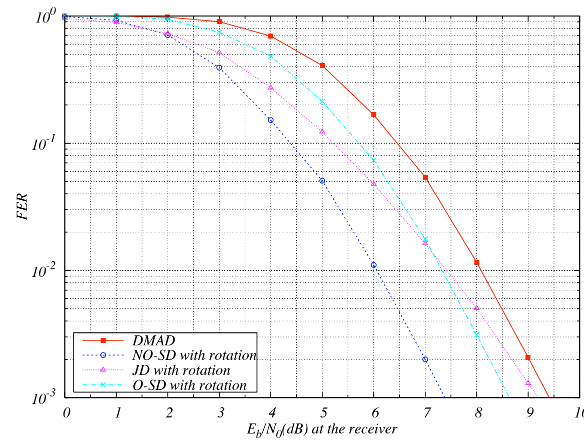

Fig. 6. Cooperative multiple-access schemes with MMSE detectors, $n_t = 2$ per user, $n_r = 4$, $N = 256$, $R_c = 1/2$ 16-state $(23, 35)_8$ NRNSC code, QPSK modulation.

respect to n_t. However, the increase in the matrix size with respect to n_r for the DMAD scheme is half than that of the NO-SD scheme. In uplink scenarios where base stations usually have more antennas than terminals, the DMAD scheme represents thus an attractive solution.

5. CONCLUSION

We presented two-user cooperative schemes for MIMO systems with three different MMSE iterative receivers. The joint detector, needing high detection complexity, has very bad performance. The separate and the distributed matrix-Alamouti detectors have excellent performance with lower detection complexity that depends on the antenna configuration, and better throughput with respect to classical cooperative protocols. The scheme based on distributed matrix-Alamouti represents an attractive candidate for uplink transmissions for both performance and complexity point of view.

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